COOPERATION FOR TRANSMISSION SCHEDULING IN WIRELESS NETWORKS

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Abstract We study the use of node cooperation as a way to improve performance in multiple-source, single-destination wireless networks that use scheduled access as the channel-access method. Unlike many other studies of scheduled access, which are based on the use of a collision channel, we use a physical channel model that incorporates other-user interference, fading, and background noise. The characteristics of such channels are exploited to enable the successful reception of multiple packets simultaneously. Our primary performance measure is throughput, which is the average number of packets that are successfully received by the destination per time slot. First, we study the performance of transmission schedules, which depends on channel fading, receiver noise, and interference. We then show that a cooperative strategy, based on the introduction of a relay to assist unsuccessful source nodes, can improve the throughput.

1 INTRODUCTION

Wireless communication networks typically operate in a complex environment that is characterized by high levels of interference, fading, and receiver noise. Although these issues present severe challenges to the design and operation of communication systems and networks, they also present opportunities that can be exploited for improved performance. Cooperative communication [4, 5, 6] is a new paradigm in which nodes cooperate by combining their resources to improve their cumulative performance. In such a strategy, the cooperating nodes may act as relays for other nodes.

Cooperative communication techniques can be implemented in a variety of ways and at several different layers of the communication/networking architecture. These techniques include virtual multiple-input multiple-output (MIMO) [9] and relay systems [1]. A cooperative approach for TDMA-based networks introduces a relay that exploits the unused channel resources to forward lost packets from earlier transmissions by other nodes [10].

In this paper, we study a wireless network in which K source nodes transmit data to a common destination. The network operates in the presence of detrimental effects such as channel fading, receiver noise, and other-user interference. An application for our model is a wireless sensor network, which consists of K sensor nodes transmitting data to a collection center. Fig. 1 shows such a network in which $K = 6$ sources transmit to a destination (D). As a cooperative strategy, in Section 5 we introduce a relay node (R) into the network with the goal of improving network performance.

Our goal is to study node cooperation for a wireless network that uses scheduling methods for accomplishing the transmissions between the source nodes and their destination. Our model is related to the TDMA-based approach of [10], which addresses relay strategies in a network that operates in an environment that is free of other-user interference. In contrast, our model, which is not limited to TDMA, deals with a network that operates in an environment that includes other-user interference.

In Section 2, we specify the model and the assumptions for the multiple-source single-destination network used in the paper. In Section 3, we present analytical methods for throughput evaluation, which incorporate the transmission schedules, network topology, and channel statistics. In Section 4, we present algorithms for constructing transmission schedules to be used by the nodes in the network. In Section 5, we study cooperation by introducing a relay node into the network. We discuss our cooperation protocol as well as opportunities for cooperation in the network. We show that the throughput performance can be significantly improved when there is an opportunity for cooperation. We summarize our contribution in Section 6.

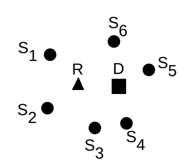

Fig. 1 A wireless network with 6 sources (S_i), a relay (R), and a destination (D)

2 NETWORK MODEL AND ASSUMPTIONS

We consider a stationary wireless network that has K source nodes, denoted by $S_1, S_2, \ldots, S_K$, that transmit their traffic to a common destination, denoted by D. An example network with $K = 6$ sources is shown in Fig. 1. We assume the following:

- The nodes, whose locations are known and fixed, are equipped with omnidirectional antennas.
- The destination can receive more than one successful transmission at a time, i.e., it has multiple reception capability.
- Each source node can communicate directly with the destination. Routing is not discussed in this paper. However, our model can be extended to include

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1. REPORT DATE **OCT 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Cooperation for Transmission Scheduling in Wireless Networks**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Information Technology Division,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
IEEE Military Communications Conference (MILCOM) 2009 Proceedings, 18-21 Oct 2009, Boston. MA.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

multi-hop communication by allowing some nodes to receive and then to transmit.

- Each source node always has traffic to transmit, i.e., its transmission queue is never empty.
- Time is divided into slots. The traffic is expressed in terms of fixed-size packets such that it takes one time slot to transmit one packet. A frame consists of M_{frame} consecutive time slots.
- Our primary performance measure is sum throughput, which is the average number of packets that are successfully received by the destination in a time slot. We do not address issues such as time delays and stability analysis in this paper.
- Nodes transmit according to a schedule, i.e., a node can transmit only in an assigned time slot.
- Each source node transmits exactly once in each frame, and that the schedule repeats from frame to frame. Thus, it is sufficient to study the performance in any one frame.

Definition 1 A *schedule* is a tuple

$$(H_1, H_2, \ldots, H_{M_{\text{frame}}})$$

where H_k is the set of source nodes that simultaneously transmit in time slot k.

Later in the paper, we present algorithms for constructing schedules, in which the frame length M_{frame} and the sets H_k are determined, $k = 1, 2, \ldots, M_{\text{frame}}$.

The network is operated based on the principle of power capture, i.e., a packet is successfully received, even in the presence of interference and noise, as long as its signal-to-interference-plus-noise ratio (SINR) exceeds a given threshold [12]. More precisely, suppose that we are given a set H of source nodes that transmit in the same time slot, and $S \in H$. Let $P_{\text{rx}}(S, D)$ be the signal power received from node S at node D, and let $\text{SINR}(S, D)$ be the SINR determined by node D due to the transmission from node S, i.e.,

$$\text{SINR}(S, D) = \frac{P_{\text{rx}}(S, D)}{P_{\text{noise}}(D) + \sum_{U \in H \setminus \{S\}} P_{\text{rx}}(U, D)}$$

where $P_{\text{noise}}(D)$ denotes the receiver noise power at node D. We assume that a packet transmitted by S is successfully received by D if

$$\text{SINR}(S, D) > \beta \tag{1}$$

where $\beta \geq 0$ is a threshold at node D, which is determined by application requirements and the properties of the network. When $\beta < 1$ (e.g., in spread-spectrum networks), it is possible for two or more transmissions to satisfy (1) simultaneously.

The wireless channel is subject to fading, as described below. Let $P_{\text{tx}}(S)$ be the transmit power at node S, and $r(S, D)$ be the distance between nodes S and D. When node S transmits, the power received by node D is modeled by

$$P_{\text{rx}}(S, D) = A(S, D) g(S, D)$$

where $A(S, D)$ is a random variable that incorporates the channel fading. We refer to $g(S, D)$ as the "received power factor," which depends on $r(S, D)$ and $P_{\text{tx}}(S)$. For far-field communication (i.e., when $r(S, D) \gg 1$), we have

$$g(S, D) = P_{\text{tx}}(S) r(S, D)^{-a} \tag{2}$$

where a is the path-loss exponent whose typical values are between 2 and 4. A simple approximate model for both near-field (i.e., when $r(S, D) < 1$) and far-field communication is

$$g(S, D) = P_{\text{tx}}(S)[r(S, D) + 1]^{-a} \tag{3}$$

where the expression $r(S, D) + 1$ is used to ensure that $g(S, D) \leq P_{\text{tx}}(S)$. Under Rayleigh fading, $A(S, D)$ is exponentially distributed [11, p. 36].

Our goal is to study methods for accomplishing the communication between the sources and destinations, and to analytically evaluate the resulting performance. Under the well-known traditional TDMA method, each source node is given a turn to transmit, i.e., there is exactly one transmission and no other-user interference in each time slot. In this paper we consider power-capture-based approaches, as described in the following sections, under which more than one transmission is allowed in a time slot.

3 THROUGHPUT EVALUATION

Consider a transmission schedule $(H_1, H_2, \ldots, H_{M_{\text{frame}}})$, where H_k is the set of source nodes that transmit in time slot k (see Definition 1). For a given time slot k, let $C^k_{H_k}(S, D)$ be the probability that a packet from source node S is successfully received by destination D, given that all the nodes in H_k simultaneously transmit in this time slot. Let $C_{\text{success}}(k)$ be the average total number of successful transmissions in time slot k. We then have

$$C_{\text{success}}(k) = \sum_{S \in H_k} C^k_{H_k}(S, D) \tag{4}$$

We now define *throughput* T to be the average number of packets that are successfully received by the destination in a time slot. Recall that there are M_{frame} time slots in a frame. Using (4), the throughput is then

$$\begin{aligned} T &= \frac{1}{M_{\text{frame}}} \sum_{k=1}^{M_{\text{frame}}} C_{\text{success}}(k) \\ &= \frac{1}{M_{\text{frame}}} \sum_{k=1}^{M_{\text{frame}}} \sum_{S \in H_k} C^k_{H_k}(S, D) \end{aligned} \tag{5}$$

For the case of Rayleigh fading, the following result (whose proof is given in [3, 7]) provides the exact formula for $C^k_{H_k}(S, D)$, which depends on the receiver noise, channel fading, receiver threshold, and other-user interference.

Theorem 1 Suppose that the fading between a transmitting node S and a receiving node D is modeled as a Rayleigh random variable Y_S with parameter $v(S,D)$. For $S \neq U$, assume that Y_S and Y_U are independent. Let $g(S,D)$ denote the received power factor, which depends on the distance and the transmit power, e.g., $g(S,D) = P_{\text{tx}}(S)\,[r(S,D)+1]^{-a}$. Given that all the nodes in H_k simultaneously transmit in time slot k, the probability that a packet from S is successfully received by D is

$$C_{H_k}^k(S,D) = \frac{\exp\left(-\frac{\beta P_{\text{noise}}(D)}{v(S,D)g(S,D)}\right)}{\prod_{U\in H_k\setminus\{S\}}\left[1+\beta\frac{v(U,D)g(U,D)}{v(S,D)g(S,D)}\right]}$$

where β and $P_{\text{noise}}(D)$ are the required SINR threshold and the receiver noise power at D, respectively.

4 BASELINE ALGORITHMS FOR SCHEDULE CONSTRUCTION

Recall that we define a schedule in terms of a frame (Definition 1). Each frame has M_{frame} time slots. The set of source nodes that transmit in time slot k is denoted by H_k. Similar to the traditional TDMA method, our capture-based method also require that each source node transmits *once* in each frame. However, our method allows the possibility of more than one transmission in a time slot, i.e., we may have $|H_k| > 1$ for some k. Under the TDMA method, we have $M_{\text{frame}} = K$ and $|H_k| = 1$ for all k, where K is the number of source nodes. Under the capture-based method, we have $1 \leq M_{\text{frame}} \leq K$ and $|H_k| \geq 1$ for all k.

Let us consider an arbitrary schedule $(H_1, H_2, \ldots, H_{M_{\text{frame}}})$. Because we require that *each* source node transmits *once* in each frame, we must have $\{S_1, S_2, \ldots, S_K\} = \cup_{k=1}^{M_{\text{frame}}} H_k$ and $H_k \cap H_l = \emptyset$ for $k \neq l$. Thus, the schedule is associated with a partition of the set of the K source nodes. The number of possible schedules is then the number of different partitions of the set of the K source nodes. This number, called the Bell number B_K [2], obeys the recursion

$$B_{n+1} = \sum_{i=0}^{n} \binom{n}{i} B_i \tag{8}$$

with $B_0 = 1$. The Bell numbers grow rapidly, e.g., $B_2 = 2$, $B_3 = 5$, $B_7 = 877$, $B_{10} = 115975$, and $B_{13} = 27644437$.

To summarize, we can compute the throughput T in (5) for each of the B_K schedules. Thus, our model and formulation naturally lead to the following schedule optimization problem: Find an optimal schedule that maximizes the throughput T.

4.1 Algorithms for Schedule Construction

We now briefly present centralized algorithms for constructing schedules used by the K source nodes for transmitting their packets to the destination (see [8] for more details). In this section, we focus on a baseline network that does not rely on cooperation (i.e., there is no relaying). In the next section, we show that network performance can be improved when there is cooperation among the nodes in the network.

Optimal Algorithm (OPT) Under OPT, we perform an exhaustive search to compute the throughput values for all B_K possible schedules, and then choose an optimal schedule that yields the maximum throughput. Here, B_K is the Bell number, which is also the number of different partitions of the set of the K source nodes [see (8)]. This number is very large, even for moderate values of K, e.g., $B_{30} \approx 8.467 \times 10^{23}$. Although OPT yields the best possible throughput, it has the disadvantage of high computational complexity. It is shown in [8] that the overall complexity of OPT is $\mathrm{O}(B_K)\times\mathrm{O}(K^2)$.

Because of the high complexity of OPT, heuristic suboptimal algorithms that have polynomial complexity are desirable. One of these heuristic algorithms is the following [8].

Algorithm 1 This algorithm has K steps, where K is the number of source nodes. At step 1, source node S_1 is scheduled for time slot 1. At step i, source node S_i is scheduled for time slot m that will result in the maximum throughput (computed up to this step). Note that m can be a slot constructed in a previous step (i.e., S_i can share the slot with some other previous nodes) or m can be a new slot. The algorithm stops at step K in which the final source node S_K is scheduled. It is shown in [8] that the overall complexity of Algorithm 1 is $\mathrm{O}(K^3)$. In this algorithm, for simplicity, the source nodes are scheduled one by one in the natural order $S_1, S_2, \ldots, S_K$. However, any other form of ordering will also work.

4.2 Performance Evaluation

In this section, we compare the throughput performance for OPT and Algorithm 1. We also show the impact of channel conditions, receiver noise level, other-user interference, network topology, and schedules on performance. We assume the following:

- The path-loss exponent is $a = 3$.
- The wireless channel is subject to Rayleigh fading with Rayleigh parameter $v(S,D) = 1$.
- The received power factor $g(S,D)$ is given by (3).
- The transmit power is $P_{\text{tx}}(S) = 1$ for all source nodes S. The receiver noise power at destination D is $P_{\text{noise}}(D) = 0.001$.

We now study a stationary wireless network as shown in Fig. 2, which has a destination D and K sources (S_i). We assume that the sources are located randomly in the circle centered at (0, 0) and of radius $r = 5$. The location of the destination is $(x_D, 0)$. In the following, we show the throughput T versus the receiver threshold β for various network sizes and topology configurations. The values of throughput are averaged over 100 random network instances.

Consider a small network with $K = 10$ source nodes. First, we let $x_D = 0$, i.e., the destination is located at the center of the circular region in which the sources are distributed. The performance results are shown in Fig. 3. Our results are evaluated for different values of the threshold β. Smaller values of β result in higher throughput T. Fig. 3 shows that, as expected, OPT (which is computationally expensive) outperforms the heuristic Algorithm 1 (which has polynomial-time complexity).

Next, we let $x_D = 10$, i.e., the destination is outside the circle of radius $r = 5$. The throughput results, which are shown in Fig. 4, are lower than those for the case $x_D = 0$. This is because the distances between the sources and the destination are larger (while the receiver noise power at destination D still maintains at $P_{\text{noise}}(D) = 0.001$), which imply that the SINR determined at the destination is now reduced.

We now consider a network with $K = 100$ nodes. It is not feasible to apply OPT, which has high computational complexity, to the network with this large size. The throughput results are shown in Fig. 5 (for $x_D = 0$ and $x_D = 10$) for our polynomial-time Algorithm 1.

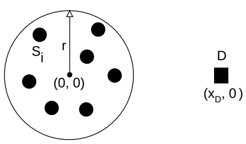

Fig. 2 A wireless network with K sources (S_i) and a destination (D)

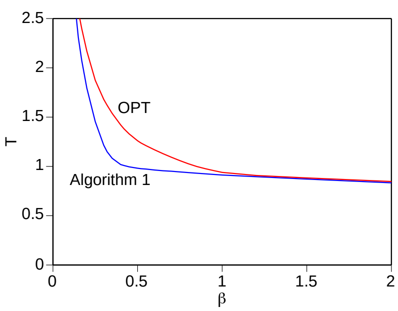

Fig. 3 Throughput (T) vs threshold (β) for $K = 10$ and $x_D = 0$

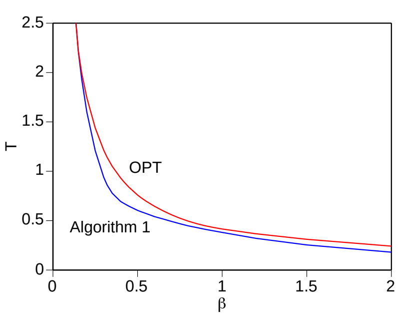

Fig. 4 Throughput (T) vs threshold (β) for $K = 10$ and $x_D = 10$

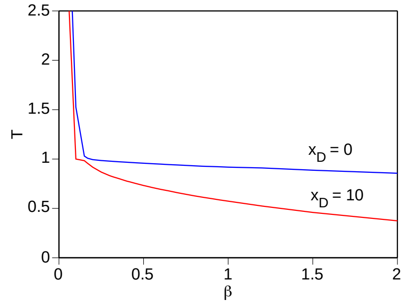

Fig. 5 Throughput (T) vs threshold (β) under Algorithm 1 ($K = 100$)

5 COOPERATION FOR PERFORMANCE IMPROVEMENT

We now use cooperation to improve throughput performance, by adding a relay node R to the network at location $(x_R, 0)$ as shown in Fig. 6. The main function of the relay is to collect packets that are not successfully transmitted by sources, and then to attempt to transmit these packets to the destination on behalf of the sources. Here, for easy understanding, we consider the use of only a single relay. However, our model can be extended to include multiple relays.

With the addition of the relay, we need the following additional assumptions:

- The relay transmission power is $P_{\text{tx}}(R) = 1$.
- The relay cannot transmit and receive at the same time, i.e., in each time slot, the relay can be in either receive state or transmit state, but not both.
- The relay transmits only if it has packets in its queue, which has infinite buffering capacity. Packets enter this queue according to the following rules. Initially, the queue is empty. Suppose that a source node transmits a packet at the beginning of a time slot k. This packet enters into the queue if both following conditions are met at the end of the time slot k: (a) the packet is received successfully by the relay and (b) the packet is not received successfully by the destination. The relay transmits the packets in its queue according to the order these packets are received.
- When a packet enters into the relay queue, the relay will take over the responsibility for forwarding this packet to the destination, i.e., the original source is no longer responsible for retransmitting this packet. Thus, there are no duplicated transmissions. A packet that is not successfully transmitted by the relay must be retransmitted by the relay at a later time slot.

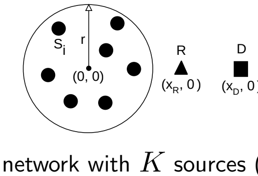

Fig. 6 A wireless network with K sources (S_i), a relay (R), and a destination (D)

5.1 Cooperation Protocol

Our relay algorithm works in an opportunistic way with the goal of improving the throughput previously obtained from the baseline algorithms. The main idea is, for a given baseline schedule, to allow the relay to cooperate (by purposely interfering) with the baseline schedule, as long as this cooperation results in higher throughput.

Relay Algorithm Suppose that a *baseline frame*, which is constructed from a baseline algorithm without using the relay, is given. For each time slot of the baseline frame, we compute the throughput that would result if the relay transmits (along with other source nodes) in this slot. If this would result in higher throughput, the relay is allowed to transmit in this slot, which is then called a *cooperative time slot*. Otherwise, the relay is not allowed to transmit in this time slot, which is then called a *baseline time slot*. Note that the cooperative and baseline time slots, which are combined to form the *cooperative frame*, can be found offline. □

Our cooperation protocol, which never underperforms the given baseline protocol, works as follows. Initially, the network operates in the baseline mode (i.e., via baseline time slots) for a number of frames. During this time, the relay is in receive state and quietly collects packets into its queue. After a sufficient number of packets enter into the queue, the network switches to the cooperative mode in which the relay transmits in cooperative time slots that are determined from our Relay Algorithm. The network stays in the cooperative mode until the relay empties its queue. The network then switches to the baseline mode, and so on. We assume that the switch between the modes always start at the beginning of a frame. Note that, under our cooperation protocol, the cooperative frame length and the order of source node transmissions remain the same as those of the baseline frame.

Let us now compare the performance between a baseline frame (i.e., there is no cooperation) and a cooperative frame (i.e., there is cooperation), under the condition that the relay always has packets in its queue to transmit in all cooperative time slots. Figs. 7 and 8 show the throughput results for two locations of the relay: $x_R = 5$ and $x_R = 8$. The destination is located at $x_D = 10$ (see Fig. 6). When $x_R = 5$, the relay is located at the mid-point between the destination and the center of the circular region in which the sources are distributed. Either location of the relay results in improved performance as compared with the baseline network, even when the OPT algorithm is used. These figures indicate that $x_R = 8$ is a better location for the relay when β is greater approximately 0.5. Thus, the cooperation in the form of relaying is clearly beneficial.

A relevant question is how often the network operates in the cooperative mode. In the following we address this question by introducing the concept of "cooperation opportunity," which refers to the fraction of time that the network operates in the cooperative mode.

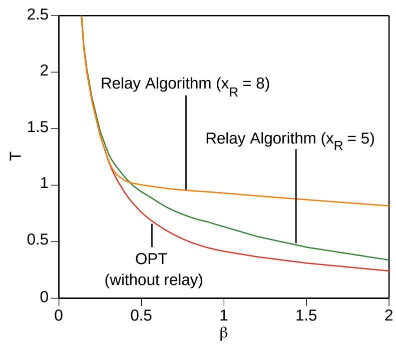

Fig. 7 Relay Algorithm is used to enhance OPT Algorithm ($K = 10$, $x_D = 10$)

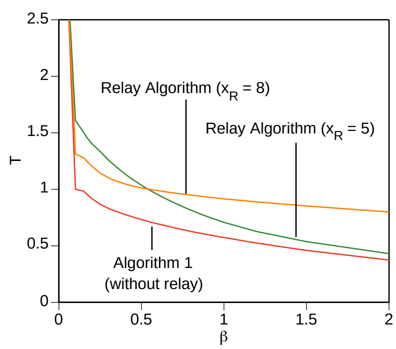

Fig. 8 Relay Algorithm is used to enhance Algorithm 1 ($K = 100$, $x_D = 10$)

5.2 Opportunities for Node Cooperation

The relay can transmit only if it has packets in its queue. Note that, for some network topology and channel statistics, it may take a long time for the relay to collect packets into its queue. Thus, it is of interest to estimate the average number of packets that enter into the queue during a frame duration.

Let A_b be the random variable representing the number of packets that enter the relay queue during a baseline frame (i.e., without cooperation). Consider a packet transmitted by source node S in time slot k. This packet is successfully received by relay R with probability $C^k_{H_k}(S, R)$, and is not successfully received by destination D with probability $1-C^k_{H_k}(S, D)$. Thus, the average number of packets entering the relay queue during a baseline frame (which has M_{frame} time slots) is

$$E(A_b) = \sum_{k=1}^{M_{\text{frame}}} \sum_{S \in H_k} C^k_{H_k}(S, R)[1 - C^k_{H_k}(S, D)] \quad (10)$$

Recall that a cooperative frame consists of two types of time slots: baseline slots in which the relay is in receive state and cooperative slots in which the relay can transmit along with transmissions from source nodes. Let F_b and F_c be the sets of baseline slots and cooperative slots, respectively, in a cooperative frame, i.e., $|F_b| + |F_c| = M_{\text{frame}}$. Let A_c be the random variable representing the number of packets that enter the relay

queue during a cooperative frame (via the slots in F_b). Similar to (10), we have

$$E(A_c) = \sum_{k \in F_b} \sum_{S \in H_k} C^k_{H_k}(S,R)[1 - C^k_{H_k}(S,D)] \quad (11)$$

Recall that during a cooperative frame, the relay transmits in cooperative slots (in addition to transmissions from source nodes). Note that a packet leaves the relay queue when it is successfully transmitted by the relay. Let Y be the random variable representing the number of packets that leave the relay queue during a cooperative frame, under the condition that there are at least $|F_c|$ packets in the queue. The average number of packets that leave the relay queue during a cooperative frame is then

$$E(Y) = \sum_{k \in F_c} C^k_{H_k \cup \{R\}}(R,D) \quad (12)$$

Let us consider a baseline-cooperative cycle that consists of $f_b + f_c$ frames, where the random variables f_b and f_c represent the number of frames for which the network operates in the baseline mode and cooperative mode, respectively. Assume here that $f_b, f_c \gg 1$. We define the network *cooperation opportunity (CO) index* to be $z = E(f_c)/[E(f_b) + E(f_c)]$, which refers to the fraction of time for which the network operates in the cooperative mode.

The average number of packets entering into the relay queue during the f_b frames is $E(f_b)E(A_b)$. In the following, we assume that $E(A_b) > 0$ and $E(f_b)E(A_b) \geq |F_c|$. The average number of packets leaving relay queue during the f_c frames is $E(f_c)E(Y)$. Note also that the average number of packets entering into the relay queue during the f_c frames is $E(f_c)E(A_c)$. If $E(A_c) \geq E(Y)$, then the relay queue size will grow to infinity, and the network will always be in the cooperative mode after a sufficient number of frames. We then have $z = 1$ in this case. Thus, in the following we assume that $E(A_c) < E(Y)$. The total average number of packets entering into the relay queue during the cycle is $E(f_b)E(A_b) + E(f_c)E(A_c)$. According to our cooperation protocol, this number approximately equals the average number of packets leaving relay queue during the f_c frames. Thus, we have $E(f_b)E(A_b) + E(f_c)E(A_c) = E(f_c)E(Y)$, which implies

$$\frac{E(f_b)}{E(f_c)} = \frac{E(Y) - E(A_c)}{E(A_b)} \quad (13)$$

Note that the network CO index can also be written as

$$z = \frac{1}{1 + E(f_b)/E(f_c)} \quad (14)$$

Substituting (13) into (14), and simplifying the result, we have

$$z = \frac{E(A_b)}{E(Y) - E(A_c) + E(A_b)} \quad (15)$$

for $E(Y) > E(A_c)$. Recall that $z = 1$ when $E(Y) \leq E(A_c)$. Thus, from (15), the network CO index can be written as

$$z = \frac{E(A_b)}{\max\{0, E(Y) - E(A_c)\} + E(A_b)} \quad (16)$$

where $E(A_b)$, $E(A_c)$, and $E(Y)$ are given in (10), (11), and (12), respectively. The network CO index given in (16) depends on channel statistics, network topology, and especially on the location of the relay.

The values of z are shown in Fig. 9 (for OPT) and Fig. 10 (for Algorithm 1) for two locations of the relay: $x_R = 5$ and $x_R = 8$. Recall that z is the fraction of time for which the network operates under the cooperative mode. Note that $z = 0$ at $\beta = 0$, and z rapidly rises for a short interval of β values. The figures show that, for the majority of β values, the z values for $x_R = 5$ are higher than those for $x_R = 8$. This is expected, because the relay is closer to the source nodes when $x_R = 5$ than when $x_R = 8$, which implies that it is more likely to successfully receive packets from the sources (than when $x_R = 8$), and less likely to successfully transmit the packets in its queue to the destination (which is located at $x_D = 10$). Thus, the relay queue is more likely to contain more packets for this case, which implies that the network is more likely to operate in the cooperative mode.

Recall that, under our cooperation protocol, the network operates by switching between the baseline mode (with fraction of time $= 1 - z$) and the cooperative mode (with fraction of time $= z$). Let T_b and T_c be the throughput values under the baseline mode and the cooperative mode, respectively. In Figs. 7 and 8, the T_b values are given by the lowest curves, while the T_c values are given by the upper curves. Thus, the overall throughput of our cooperation protocol is $T_{\text{overall}} = (1 - z)T_b + zT_c$. The T_{overall} values, along with the T_b values, are shown in Figs. 11 and 12 for the two locations of the relay: $x_R = 5$ and $x_R = 8$. Once again we see that $x_R = 8$ is a better location for the relay for larger values of β. However, the degree of improvement is less than that shown in Figs. 7 and 8, because a significant smaller fraction of frames are cooperative when $x_R = 8$ than when $x_R = 5$ for $\beta > 0.5$ as shown in Figs. 9 and 10.

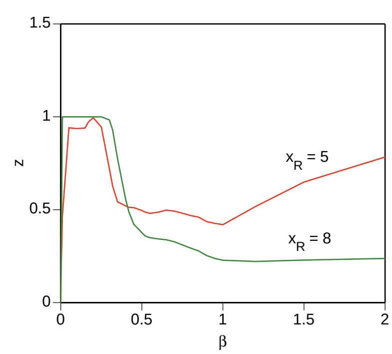

Fig. 9 Cooperation opportunity for OPT Algorithm ($K = 10$, $x_D = 10$)

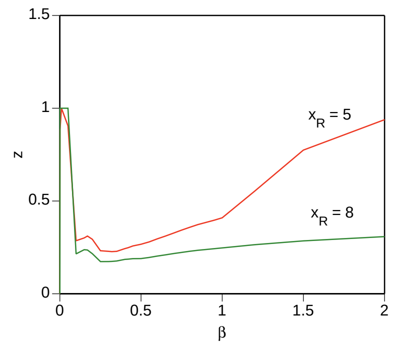

Fig. 10 Cooperation opportunity for Algorithm 1 ($K = 100$, $x_D = 10$)

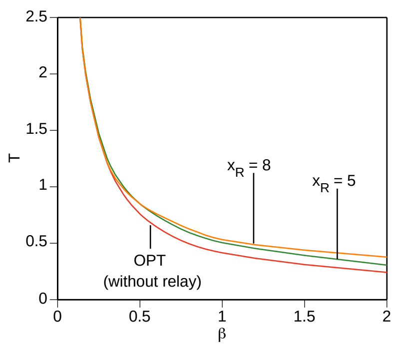

Fig. 11 Throughput with and without cooperation protocol for OPT Algorithm ($K = 10$, $x_D = 10$)

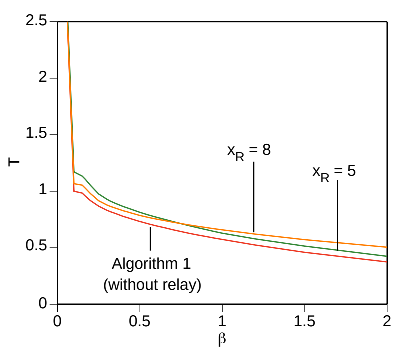

Fig. 12 Throughput with and without cooperation protocol for Algorithm 1 ($K = 100$, $x_D = 10$)

6 SUMMARY

The packetized, multiple-source, single-destination wireless network considered in this paper operates under the power-capture principle, as well as under realistic conditions such as receiver noise, fading, and other-user interference. Scheduled access is an effective method for accomplishing the transmissions between the source nodes and the destination. Our proposed transmission scheduling creates opportunities for node cooperation in the form of relaying in the network. For any given frame of our cooperation protocol, the network operates either in the cooperative mode or in the baseline mode. Under the baseline mode, the relay quietly collects traffic packets from the source nodes. The network then switches to the cooperative mode after the relay collects a sufficient number of packets for its transmissions. The throughput performance, even for optimal scheduling, can be improved under the cooperation protocol.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research.

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